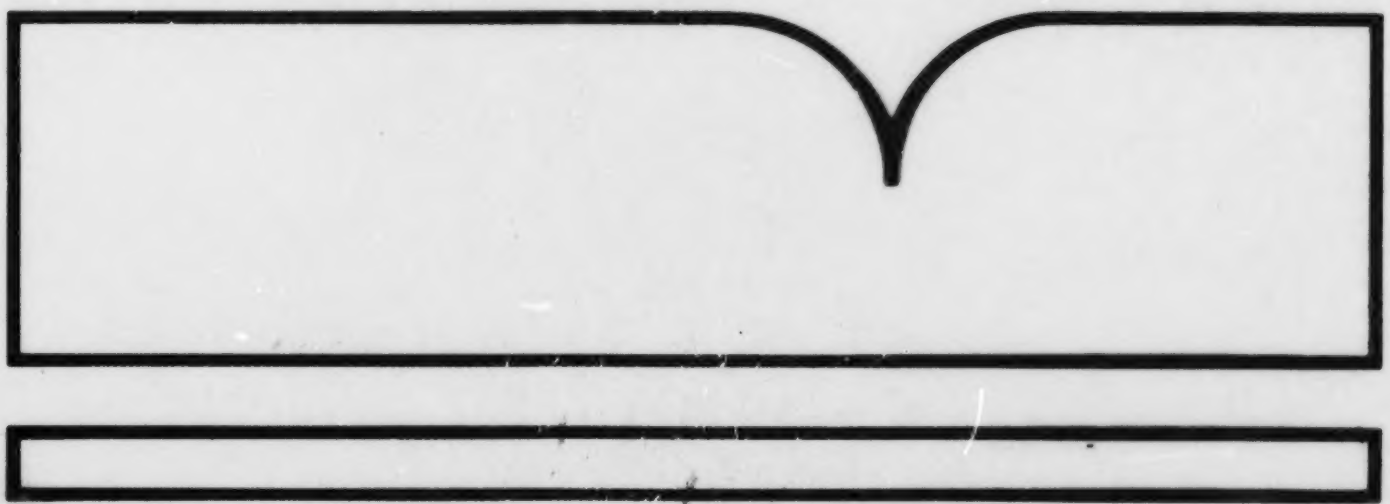
PB84-101716

Air Quality Data Analysis System for Interrelating Effects, Standards, and Needed Source Reductions: Part 7 An 03-SO2 Leaf Injury Mathematical Model

(U.S.) Environmental Sciences Research Lab.
Research Triangle Park, NC

1983



U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completir

1. REPORT NO.	2.	3. R
EPA-600/J-83-057		PB84-101716

4. TITLE AND SUBTITLE	5. REPORT DATE
AN AIR QUALITY DATA ANALYSIS SYSTEM FOR INTERRELATING EFFECTS, STANDARDS, AND NEEDED SOURCE REDUCTIONS: PART 7. AN O_3-SO_2 LEAF INJURY MATHEMATICAL MODEL (Journal Version)	1983
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
R. I. Larsen, A. S. Heagle, and W. W. Heck	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
USEPA, Research Triangle Park, NC 27711, and USDA, North Carolina State U, Raleigh, NC 27650	CDTA1D/04-1315(FY-83)
	11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
Environmental Sciences Research Laboratory -- RTP, NC Office of Research and Development U. S. Environmental Protection Agency Research Triangle Park, NC 27711	14. SPONSORING AGENCY CODE EPA/600/09

15. SUPPLEMENTARY NOTES

REF: APCA Journal, 33(3):198-209, March 1983

16. ABSTRACT

Leaf injury data from acute and chronic exposure studies of Dare soybean were regressed against the logarithms of exposure time and O_3 and SO_2 concentrations to develop a new two-pollutant leaf injury model (which explains 88% of the variance) and to calculate the parameters of best fit for this new model and a previously developed one-pollutant model. Using the calculated parameters, the percentage of leaf surface injured over a growing season by O_3, SO_2, or both simultaneously was estimated for an ambient air sampling site located 2 miles from a coal-burning power plant. For this site, the one- and two-pollutant models predicted that SO_2 effects would be negligible if SO_2 concentrations never exceeded the National Ambient Air Quality Standard (NAAQS) of 0.50 ppm, averaged over 3 h. However, calculations suggest that O_3 may injure up to 24% of Dare soybean leaf surface over a growing season even though the O_3 NAAQS of 0.12 ppm, averaged over 1 h, is never exceeded. Because the 3 h SO_2 standard is exceeded at very few places, the O_3 model is usually sufficient to estimate Dare soybean leaf injury. Leaf injury is estimated by taking the logarithm of the summation of each daytime hour's exponentiated O_3 concentration (c) measured at an ambient air sampling site over a growing season.

$$z = -0.0828 + 0.4876 \ln \left(\sum c_{O_3}^{2.618} \right)$$

where z is the Gaussian transform of percent leaf injury.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
RELEASE TO PUBLIC	UNCLASSIFIED	11
	20. SECURITY CLASS *(This page)*	22. PRICE
	UNCLASSIFIED	

EPA Form 2220-1 (9-73)

EPA-600/J-83-057
JOURNAL ARTICLE

Reprinted from **APCA JOURNAL**, *Vol. 33, No. 3, March, 1983*
198-209

An Air Quality Data Analysis System for Interrelating Effects, Standards, and Needed Source Reductions: Part 7. An O_3–SO_2 Leaf Injury Mathematical Model

Ralph I. Larsen
U.S. Environmental Protection Agency
Research Triangle Park, North Carolina

Allen S. Heagle and Walter W. Heck
U.S. Department of Agriculture
North Carolina State University
Raleigh, North Carolina

Leaf injury data from acute and chronic exposure studies of Dare soybean were regressed against the logarithms of exposure time and O_3 and SO_2 concentrations to develop a new two-pollutant leaf injury model (which explains 88% of the variance) and to calculate the parameters of best fit for this new model and a previously developed one-pollutant model. Using the calculated parameters, the percentage of leaf surface injured over a growing season by O_3, SO_2, or both simultaneously was estimated for an ambient air sampling site located 2 miles from a coal burning power plant. For this site, the one- and two-pollutant models predicted that SO_2 effects would be negligible if SO_2 concentrations never exceeded the National Ambient Air Quality Standard (NAAQS) of 0.50 ppm, averaged over 3 h. However, calculations suggest that O_3 may injure up to 24% of Dare soybean leaf surface over a growing season even though the O_3 NAAQS of 0.12 ppm, averaged over 1 h, is never exceeded. Because the 3 h SO_2 standard is exceeded at very few places, the O_3 model is usually sufficient to estimate Dare soybean leaf injury. Leaf injury is estimated by taking the logarithm of the summation of each daytime hour's exponentiated O_3 concentration (c) measured at an ambient air sampling site over a growing season. This is expressed as: $z = -0.0828 + 0.4876 \ln \{\Sigma c_{O_3}^{2.618}\}$, where z is the Gaussian transform of percent leaf injury. The methods developed in this paper, using Dare soybean data as an example, may apply to other plants.

The primary purpose of this paper (which is part of a series[1-6]) is to develop a mathematical model that expresses percent leaf injury as a function of simultaneous exposures to O_3 and SO_2. This new two-pollutant model is based on previously reported data for soybean.[7] A secondary purpose is to use this two-pollutant model and a previously developed one-pollutant model[3] to estimate cumulative leaf injury for soybean exposed to ambient O_3, SO_2, or both over a growing season. These results are compared with crop reduction measurements determined in other ways.[8]

Development of Mathematical Models

Equations (mathematical models) can be fitted to data that plot as either curved lines or straight lines. Curved lines can be fitted by polynomials or Fourier analysis. Some curved plots can be straightened by plotting transformed data, such as the logarithm of a variable, which is the approach used in this series of papers. The approach used here is similar to probit analysis.

Although air pollutant concentration data may be fit to a variety of distributions, these data are often transformed to their logarithms, and the percentage of time (frequency) that stated concentrations are exceeded is often transformed to a Gaussian (normal) variable, z_t. Plots of concentration versus frequency often approximate straight lines when plotted on log-probability graph paper.[1,2,4,6]

Plots of percent leaf injury versus air pollutant concentration[3] and of percent excess mortality in mice, first exposed to nitrogen dioxide (NO_2) and then to a lung pathogen,[5] also often approximate straight lines on log-probability graph paper. Plots of these percentage responses against exposure time also yield approximately straight lines. In fact, when the responses of many animals and plants to various toxicants are plotted against exposure time or concentration on log-probability graph paper, the plots are often approximately linear.[9]

The dependent variable for all of these applications has been percentage, transformed to a Gaussian linear variable, z (the number of standard deviations from the median). For air pollutant concentrations, the percentage used has been the percentage of time that a stated concentration is exceeded. For leaf injury, percentage has been the percentage of leaf surface injured. For mouse mortality, percentage has been the percentage of excess mortality in mice first exposed to NO_2 and then to a lung pathogen when compared with mice exposed only to a lung pathogen.

The two independent variables for all of these applications have been the logarithms of air pollutant concentration and time. Previously, only one air pollutant at a time has been studied. In this study the effects of the concentrations of two pollutants to which a plant is exposed simultaneously are also studied and modeled.

Air Pollution Control Association

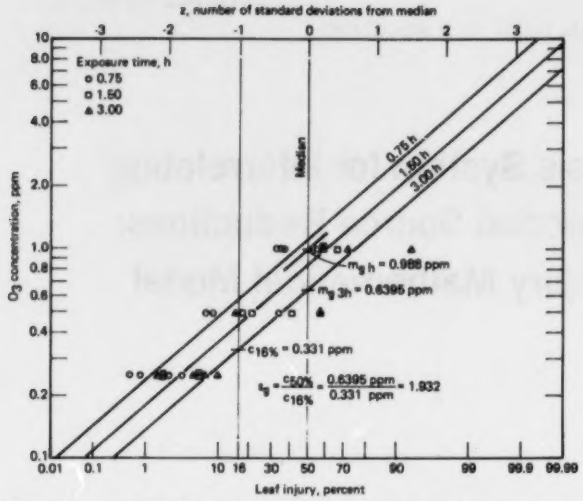


Figure 1. Percent leaf injury in Lee 68 and Dare soybeans exposed to 0.25, 0.50, or 1 ppm O_3 for 0.75, 1.5, or 3 h.

Leaf Injury Models

Plants can be injured by either acute or chronic exposures to air pollutants. O'Gara developed the first acute plant injury equation in 1922 to express SO_2 injury.[10] His is a linear equation which has since been modified by Thomas and Hill,[11] Guderian *et al.*,[12] Zahn,[13] and Heck and Tingey.[14]

Heck *et al.*[15] compared the Heck-Tingey (H-T)[14] and Larsen-Heck (L-H)[3] acute leaf injury models. Both models have three variables (concentration, time, and leaf injury) and three calculated constant parameters. The H-T model is linear; the L-H model is non-linear (log-probabilistic). The data used to compare the two models resulted from the exposure to O_3 of six plant species: (Calabrese) broccoli, (Roma) tomato, (Pennscott) red clover, (Martin) sorghum, (Northland) spinach, and (Long Marketer) cucumber. The L-H model left an average of 14% of the variance unexplained. The H-T model left 3.5 times as much, 49%, unexplained. Therefore, the L-H model fit the plant injury data much better than did the H-T model. Other non-linear models (e.g., a logistic model) would probably give similar results. The L-H model has been applied to measurements of leaf injuries caused by acute O_3 exposures for 19 sensitive, 17 intermediate, and 7 resistant plants.[15]

In this study, acute exposures are defined as 12 h or less and chronic exposures as more than 12 h. Only daytime hours (6:00 A.M.–6:00 P.M., always standard time) are considered here since the soybean plants studied are much less sensitive to pollutants at night when their stomata are nearly closed. The acute data used in developing the models are from single exposures to SO_2, O_3, or both simultaneously for 0.75, 1.5, or 3 h. In addition, chronic exposure (up to 552 h) data for O_3 were analyzed and modeled together with acute O_3 data to produce a single acute-chronic O_3 leaf injury model.

Acute Leaf Injury Data

The experimental procedures used in this study to produce the acute leaf injury data are described elsewhere.[7] Briefly, 21–26 days after planting, Lee 68 and Dare soybeans were exposed to O_3 (0.25, 0.5, or 1.0 ppm), or to SO_2 (0.5, 1.0, or 1.5 ppm), or to both simultaneously for 0.75, 1.5, or 3 h. Five

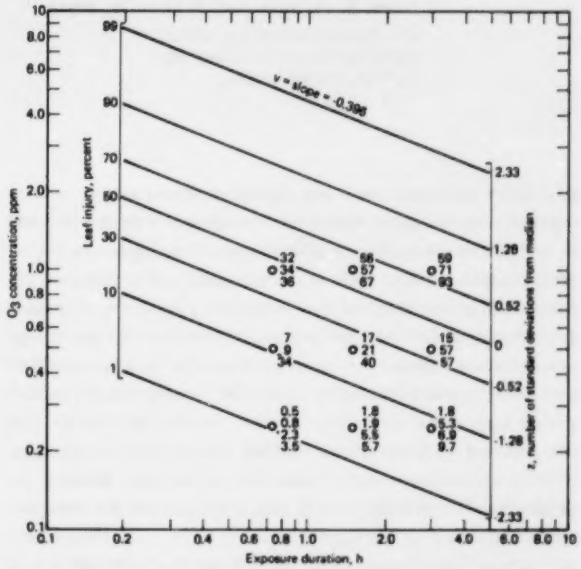


Figure 3. Percent leaf injury in Lee 68 and Dare soybeans exposed for 0.75, 1.5, or 3 h to 0.25, 0.5, or 1 ppm O_3.

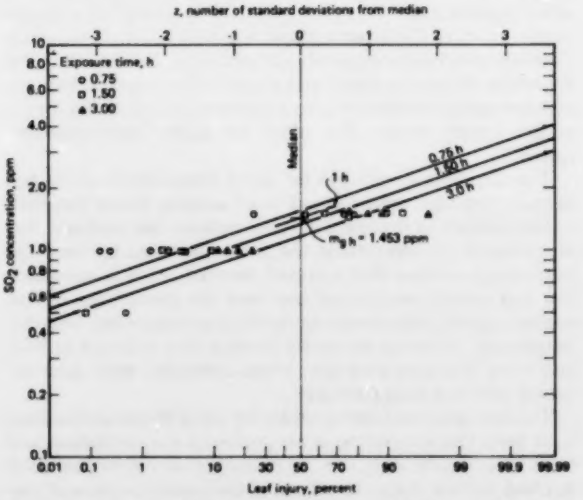


Figure 2. Percent leaf injury in Lee 68 and Dare soybeans exposed to 0.5, 1, or 1.5 ppm SO_2 for 0.75, 1.5, or 3 h.

plants of both cultivars were exposed to these treatments in two iterations of up to five experimental runs (Table I, column 7). Two days after exposure, percent leaf injury was estimated visually in 5% increments (0–100%) for each of the two primary leaves and for the oldest trifoliate leaf on each plant. Mean percent leaf injury was then calculated (column 5). Each leaf injury data point value is the mean for 60 leaves (2 cultivars, 5 plants/cultivar, 3 leaves/plant, 2 iterations of each run; $2 \times 5 \times 3 \times 2 = 60$).

Nomenclature

The nomenclature used here is basically the same as that used throughout this series of papers:

- 1 = SO_2
- 2 = O_3
- p = pollutant
- z = the number of standard deviations (top axis, Figures 1, 2) that an observed percent leaf injury (bottom axis, Figures 1, 2) is away from the median (50%)

c = concentration, in ppm

t = exposure time, in h (bottom axis, Figure 3)

LL = lower limit concentration line for pollutant 1 (Figures 4–6)

UL = upper limit concentration line for pollutant 1 (Figures 4–6)

I = impact (to be defined later)

The dependent variable is z and the natural logarithms of c and t are the independent variables used to calculate, by

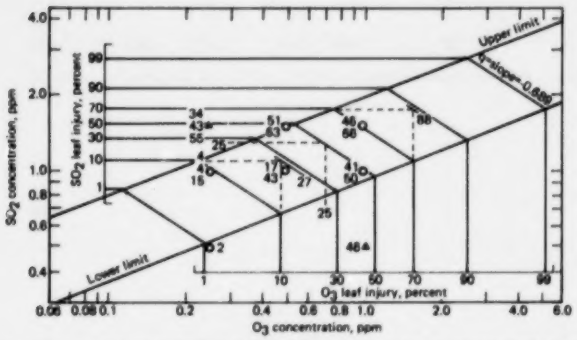


Figure 4. Percent leaf injury in Lee 68 and Dare soybeans exposed for 0.75 h to SO_2, O_3, or both.

multiple linear regression analyses, all of the following constant parameters:

m_{gh} = the geometric mean concentration; on a regression line for a 1 h exposure it is the concentration at which 50% leaf injury is plotted (Figures 1, 2)

s_g = the standard geometric deviation; on a regression line it is the concentration which indicates 50% injury divided by the concentration which indicates 16% injury (Figure 1)

u = the slope of lines with the same percent leaf injury (equal injury lines) for pollutant 1 when plotted on logarithmic paper with a vertical concentration axis and a horizontal time axis

v = the same as u, for pollutant 2 (Figure 3)

w = the same as u, for the two-pollutant model

q = the slope of equal injury lines when pollutant 1 concentration (vertical axis) and pollutant 2 concentration (horizontal axis) are plotted on logarithmic graph paper (the slope of the short diagonal lines in Figures 4–6)

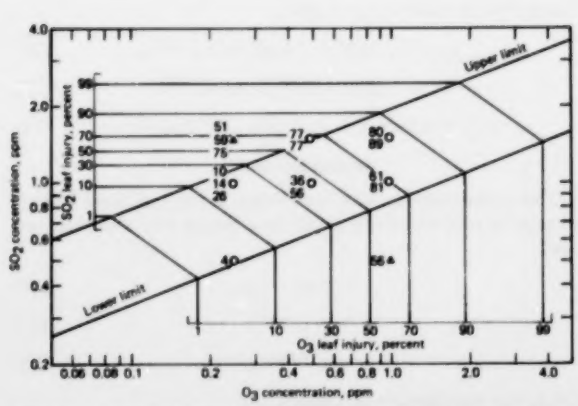


Figure 5. Percent leaf injury in Lee 68 and Dare soybeans exposed for 1.5 h to SO_2, O_3, or both.

Equations for the One- and Two-Pollutant Leaf Injury Models

The Three Basic Equations

The L-H one-pollutant model[3] can be expressed for SO_2 and O_3 as follows:

$$c_1 = m_{gh1} s_{g1}{}^{z_1} t^u \quad (1)$$

$$c_2 = m_{gh2} s_{g2}{}^{z_2} t^v \quad (2)$$

Later analyses here show that this one-pollutant model can be expanded to a two-pollutant model (Eq. 3) by appending the concentration of a second pollutant and its exponent.

$$c_{p1} = m_{ghp1} s_{gp1}{}^{z_{1,2}} t^w c_{p2}{}^q \quad (3)$$

In Eq. 10 and 11 the z from Eq. 3 will be set equal to the z from Eq. 1 and 2. Therefore, subscripts p1 and p2 are used to differentiate parameters in Eq. 3 from those in Eq. 1 and 2. All of the concepts and equations presented here are based on these three equations.

The dependent variable in each of these three equations is z. Each equation can be expressed as a function of z by taking natural logarithms.

$$z_1 = (\ln c_1 - u \ln t - \ln m_{gh1})/\ln s_{g1} \quad (4)$$

$$z_2 = (\ln c_2 - v \ln t - \ln m_{gh2})/\ln s_{g2} \quad (5)$$

$$z_{1,2} = (\ln c_{p1} - q \ln c_{p2} - w \ln t - \ln m_{ghp1})/\ln s_{gp1} \quad (6)$$

The independent variables in Eq. 6 are $\ln c_{p1}$, $\ln c_{p2}$, and $\ln t$. In this equation the constant parameters, calculated by regression analyses, are q, w, m_{ghp1}, and s_{gp1}.

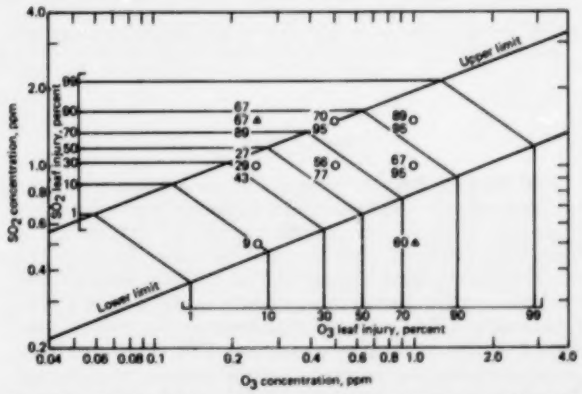


Figure 6. Percent leaf injury in Lee 68 and Dare soybeans exposed for 3 h to SO_2, O_3, or both.

Regression Analyses

A stepwise least squares multiple linear regression computer subroutine was used to calculate the parameters of best fit for Eq. 1–3 (Table I, lines 1–3, columns 10–13).

$$c_1 = 1.453\ (1.293)^{z_1} t^{-0.189} \quad (7)$$

$$c_2 = 0.988\ (1.932)^{z_2} t^{-0.396} \quad (8)$$

$$c_{p1} = 0.874\ (2.044)^{z_{1,2}} t^{-0.542} c_{p2}{}^{-0.689} \quad (9)$$

These equations have been used to calculate and plot lines for equal exposure durations (equal time lines) (Figures 1, 2) and equal injury lines (Figures 3–6). The observed mean percent leaf injury values (e.g. Table I, column 5) were plotted (Figures 1, 2) and annotated, after rounding to one or two digits (Figures 3–6).

Table I. Observations and calculated injury equation parameters for Lee 68 and Dare soybeans exposed acutely to SO_2 (pollutant 1), or to O_3 (pollutant 2), or to both simultaneously.

Observations									Calculated injury equation parameters				
		Conc, ppm							Pollutant 1		Injury eqn slope on axis		
Plant (1)	Exposure duration, h (2)	Poll 1 (3)	Poll 2 (4)	Leaf injury, %* (5)	Number of deviat, z (6)	Run (7)	Number of pollutants (8)	Number of data points (9)	Geometric mean, ppm (10)	s_g (11)	Time (12)	P2 conc (13)	Multiple correl coeff (14)
1.00	Soybeans exposed to SO_2						1	26	1.453	1.293	-.189		.877
2.00	Soybeans exposed to O_3						1	30	.988	1.932	-.396		.925
3.00	Soybeans exposed to SO_2(P1) + O_3(P2)						2	36	.874	2.044	-.542	-.689	.938
1.00	.75	1.50	.00	52.00	.05	4	1						
1.00	1.50	.50	.00	.08	-3.16	3	1						
1.00	1.50	1.00	.00	9.33	-1.32	5	1						
1.00	3.00	1.00	.00	23.92	-.71	1	1						
1.00	3.00	1.50	.00	83.67	.98	4	1						
1.00	Soybeans exposed to SO_2						1	5	1.440	1.346	-.173		.990
2.00	.75	.00	.25	.75	-2.43	1	1						
2.00	.75	.00	1.00	36.42	-.35	2	1						
2.00	1.50	.00	.50	20.58	-.82	1	1						
2.00	3.00	.00	.25	6.92	-1.48	1	1						
2.00	3.00	.00	1.00	71.00	.55	2	1						
2.00	Soybeans exposed to O_3						1	5	1.103	1.960	-.449		.999
3.00	.75	1.00	1.00	50.25	.01	4	2						
3.00	.75	1.50	.50	51.00	.02	2	2						
3.00	1.50	.50	.25	3.58	-1.80	3	2						
3.00	1.50	1.00	1.00	61.42	.29	4	2						
3.00	3.00	1.00	.25	43.33	-.17	1	2						
3.00	3.00	1.50	1.00	94.75	1.62	2	2						
3.00	Soybeans exposed to SO_2(P1) + O_3(P2)						2	6	.928	1.827	-.426	-.466	.998

* Each value is the mean leaf injury for 60 leaves (2 primary and the first trifoliate on 5 plants each of Lee 68 and Dare soybeans in 2 iterations of each run; 3 x 5 x 2 x 2 = 60 leaves)

Model Limits

The two long diagonal lines in Figures 4–6 define the concentration limits of the two-pollutant model. Above the upper limit line (*UL*), the one-pollutant model for SO_2 should be used; below the lower limit line (*LL*), the one-pollutant model for O_3 should be used. The correlation between measured and modeled z values for the two-pollutant model is 0.938 (Table I, column 14). The variance explained by this model is the square of the correlation coefficient, 88%. Thus, the two-pollutant model leaves only 12% of the variance unexplained. Two-pollutant data are also available outside of the plotted limits, at SO_2 = 1.5 ppm and O_3 = 0.25 ppm, and at SO_2 = 0.5 ppm and O_3 = 1.0 ppm. When these out of bounds data (plotted as triangular points in Figures 4–6) are included in the two-pollutant model, almost twice as much variance (21%) is left unexplained. Visual examination indicates that these out of bounds data fit the one-pollutant models quite well.

To determine the equations of the upper and lower limit lines, Eq. 1–3 were first rearranged to solve for z, giving Eq. 4–6. The equation of the lower limit line was then determined by setting $z_2 = z_{1,2}$ and solving for c_1.

$$c_{1LL} = [m_{ghp1} c_2^{q} t^{w}] \times [c_2/(m_{gh2} t^{v})]^{(\ln s_{gp1})/(\ln s_{g2})} \quad (10)$$

Similarly, the equation for the upper limit line was determined by setting $z_1 = z_{1,2}$ and solving for c_1.

$$c_{1UL} = [m_{ghp1} c_{p2}^{q} t^{w}]^{(\ln s_{g1})/(\ln s_{g1} - \ln s_{gp1})} \times [m_{gh1} t^{u}]^{(\ln s_{gp1})/(\ln s_{gp1} - \ln s_{g1})} \quad (11)$$

Using the parameters in Table I,

$$c_{1LL} = 0.8855\, c_2^{0.3966}\, t^{-0.11211} \quad (12)$$

$$c_{1UL} = 1.9326\, c_2^{0.3867}\, t^{0.00908} \quad (13)$$

Injury Equations

Solving for the expected hour by hour impact of ambient pollutant concentrations is easier if time is linearized (has no exponent) in Eq. 4–6 by expressing the z values as

$$z_1 = -(\ln m_{gh1})/(\ln s_{g1}) - (u/\ln s_{g1}) \ln(c_1^{-1/u} t) \quad (14)$$

$$z_2 = -(\ln m_{gh2})/(\ln s_{g2}) - (v/\ln s_{g2}) \ln(c_2^{-1/v} t) \quad (15)$$

$$z_{1,2} = -(\ln m_{ghp1})/(\ln s_{gp1}) - (w/\ln s_{gp1}) \ln(c_{p1}^{-1/w} c_{p2}^{q/w} t) \quad (16)$$

Using the parameters in Table I,

$$z_1 = -1.4540 + 0.7355 \ln(c_1^{5.291} t) \quad (17)$$

$$z_2 = 0.0183 + 0.6013 \ln(c_2^{2.525} t) \quad (18)$$

$$z_{1,2} = 0.1884 + 0.7581 \ln(c_{p1}^{1.845} c_{p2}^{1.271} t) \quad (19)$$

Impact Equations

The concentration and time terms in each of these last six equations can be grouped together into a new variable: impact.

$$I_1 = c_1^{-1/u} t \quad (20)$$

$$I_2 = c_2^{-1/v} t \quad (21)$$

$$I_{1,2} = c_{p1}^{-1/w} c_{p2}^{q/w} t \quad (22)$$

Using the parameters in Table I,

$$I_1 = c_1^{5.291} t \quad (23)$$

$$I_2 = c_2^{2.525} t \quad (24)$$

$$I_{1,2} = c_{p1}^{1.845} c_{p2}^{1.271} t \quad (25)$$

Eq. 17–19 can be expressed in terms of impact.

$$z_1 = -1.4540 + 0.7355 \ln I_1 \quad (26)$$

$$z_2 = 0.0183 + 0.6013 \ln I_2 \quad (27)$$

$$z_{1,2} = 0.1884 + 0.7581 \ln I_{1,2} \quad (28)$$

Eq. 14–25 can be rearranged to solve for impact as a function of z.

$$I_1 = m_{gh1}^{-1/u} s_{g1}^{-z/u} \quad (29)$$

$$I_2 = m_{gh2}^{-1/v} s_{g2}^{-z/v} \quad (30)$$

$$I_{1,2} = m_{ghp1}^{-1/w} s_{gp1}^{-z/w} \quad (31)$$

Using the parameters in Table I,

$$I_1 = 7.2202\ (1.293)^{5.291z} \quad (32)$$

$$I_2 = 0.9700\ (1.932)^{2.525z} \quad (33)$$

$$I_{1,2} = 0.7800\ (2.044)^{1.845z} \quad (34)$$

Applying the Models to Data from Experimental Exposures

Dosage versus Impact

Dosage is defined mathematically as concentration multiplied by time (ct). Dosage is proportional to the total number of pollutant molecules to which an organism is exposed over an exposure duration. If the organism remains open to exposure, emits no absorbed pollutant molecules, and detoxifies no absorbed pollutant molecules, then the resulting concentration of pollutant molecules in the target organs of the organism will be proportional to dosage.

Impact is defined mathematically above (Eq. 20–22) as exposure time multiplied by concentration(s) raised to an exponent. Physiologically, impact is the effective dosage. Impact is related to a plant's response to a pollutant (Eq. 23–25). The greater the exponent of c is, the greater is the effect of concentration as compared with time. A high exponent for c suggests that a plant has been able to resist the time effects of a pollutant exposure by responses that partially reduce the concentration of a toxicant in the target organs of a plant. The plant probably accomplishes this by various means, such as closing its stomata, emitting absorbed molecules of the pollutant, or detoxifying the pollutant. The high value of the exponent for c in Eq. 23, 5.291, indicates that concentration has a much greater effect than time on soybean plants exposed to SO_2.

Table II. Exposure durations calculated to injure 1, 5, 25, or 50% of leaf surface for Lee 68 and Dare soybeans exposed to various concentrations of SO_2 or O_3.

Pollutant	Conc, ppm	Exposure duration, h, calculated to injure stated percent of soybean leaf surface: 1%	5%	25%	50%
SO_2	0.3	178	450	1687	4218
	0.4	39	98	368	921
	0.5	12	30	113	283
	0.6	5	12	43	108
	0.7	2	5	19	48
	0.8	1	3	9	24
	0.9	0.5	1.3	5	13
	1.0	0.3	0.8	2.9	7
	1.1	0.2	0.5	1.7	4
	1.2	0.1	0.3	1.1	3
	1.3	0.1	0.2	0.7	2
	1.4	0.1	0.1	0.5	1
O_3	0.04	69	213	1071	3288
	0.06	25	77	385	1181
	0.08	12	37	186	571
	0.10	7	21	106	325
	0.12	4	13	67	205
	0.14	3	9	45	139
	0.16	2	6	32	99
	0.18	2	5	24	74

Threshold Concentrations

Plots of leaf injury data suggest that no visible injury will occur to these plants until a fairly high SO_2 concentration "threshold" is reached; then small increases in SO_2 concentrations will cause large injuries. The high injury threshold can be seen in Figure 2. Only 0.01% leaf injury is expected after 0.45 ppm of SO_2 for 3 h (Eq. 17). As concentration increases, injury increases rapidly, until 50% leaf injury is expected after 3 h of 1.2 ppm. Less than a threefold increase in concentration thus causes injury to jump from almost no injury (0.01%) to 50% injury. This relationship is expressed mathematically by the small standard geometric deviation of 1.293, which is the antilog of the slope of the equal time lines in Figure 2.

The soybeans responded almost oppositely to O_3, as indicated by the higher standard geometric deviation of 1.932 and the resulting steeper injury lines on Figure 1. Injury of 0.01% is expected after a 0.75 h exposure to the low O_3 concentration of only 0.10 ppm. Injury then increases slowly as concentration increases. A large, eleven-fold increase in concentration, to 1.1 ppm, is needed to go from 0.01% injury to 50% injury.

The one-pollutant model equations (Eq. 7–8) can be rearranged to solve for the time duration expected to injure a given percentage of leaf surface at a given concentration (Table II). For example, either 30 h at 0.5 ppm of SO_2 or 0.8 h at 1.0 ppm is expected to injure 5% of Lee 68 or Dare soybean leaf surface. Similarly, either 77 h at 0.06 ppm of O_3 or 13 h at 0.12 ppm is expected to cause 5% injury.

Injuries from Two Pollutants

The two-pollutant model (Eq. 19) predicts that leaf injury is a function of SO_2 concentration raised to an exponent times O_3 concentration raised to an exponent. The net effect (Figure 4, dashed lines) is that an SO_2 concentration predicted to cause 25% injury coupled with an O_3 concentration predicted to cause 25% injury is expected to cause 50% injury, exactly additive. For lower concentrations the effects are expected to be greater than additive (e.g., dashed lines, 10% + 10% = 27%). For higher concentrations the effects are expected to be less than additive. The two-pollutant model agrees well with the experimental results plotted in Figures 4–6. As mentioned earlier, the model explains 88% of the variance in the measured z values.

Applying the Models to Acute Ambient Exposures

Since time is linear in Eq. 23–25, the cumulative impact of pollutant concentrations can be calculated by summing each hour's exponentiated concentration. This was done for SO_2 concentrations measured for each daytime hour of April 17, 1977 (day 107), 2 miles NE of the coal burning Johnsonville steam plant in Humphreys County, TN (Table III, column 7). The O_3 data were measured at a site in Nashville, TN, and are used in this example as the expected O_3 concentrations near the steam plant. The ambient concentration data are from the National Aerometric Data Bank (NADB).

Table III. Cumulative leaf injury for Lee 68 and Dare soybeans, estimated from hourly impacts of ambient concs of SO_2 (pollutant 1) and O_3 (pollutant 2) for following year, sites, and day:
Year 1977 P1 concs are from site 441540020N02, 2.0 mi NE of Johnsonville steam plant, Humphreys Co., TN.
Year 1977 P2 concs are from site 442540011G01, 1015 Trinity Lane, Nashville, TN.

		Conc, ppm		Poll 1 limits.		Impact			Accumulation		
Day (1)	Hour (2)	Poll 1 (3)	Poll 2 (4)	Lower (5)	Upper (6)	Poll 1 (7)	Poll 2 (8)	Poll 1,2 (9)	Imp2eq (10)	z (11)	Injury, % (12)
107	7	.00	.002	.0753						-9.403	
107	8	.00	.005	.1083			.000002		.000002	-7.969	
107	9	.02	.025	.2051			.000090		.000092	-5.572	
107	10	.07	.035	.2343			.000211		.000302	-4.855	
107	11	.11	.050	.2699			.000518		.000821	-4.254	.001
107	12	.04	.065	.2995			.001005		.001826	-3.773	.008
107	13	.96	.070	.3085	.6912	.805744			.070683	-1.575	5.764
107	14	.69	.070	.3085	.6912			.017161	.086679	-1.452	7.322
107	15	.10	.070	.3085			.001212		.087891	-1.444	7.439
107	16	.00	.065	.2995			.001005		.088896	-1.437	7.536
107	17	.00	.065	.2995			.001005		.089902	-1.430	7.632
107	18	.00	.040	.2471			.000295		.090197	-1.428	7.660
Total impact for day						.946153	.007768	.049779	.090197		
z						-1.495	-2.903	-2.086	-1.428		
Injury, %						6.749	.185	1.848	7.660		

The impact of the thirteenth hour's SO_2 concentration, 0.96 ppm (column 3), was 0.81 (column 7; Eq. 23). The total impact of SO_2 for all 12 daytime hours was 0.95. Using the one-pollutant model, this gave a z_1 of −1.495 (Eq. 26). This z_1 value was translated with a computer subroutine to 6.7% leaf injury. The total impact (column 8) of O_3 concentrations (column 4) for that day was 0.0078 (Eq. 24); this gave a prediction of only 0.19% leaf injury. When the two-pollutant model (column 9) was used for each hour, the total impact was 0.050 (Eq. 25), and 1.8% injury was predicted.

The limit equations (Eq. 12–13) can be used to determine whether the SO_2, O_3, or O_3–SO_2 model should be used to calculate impact for an hour. The twelfth hour O_3 concentration of 0.065 ppm (column 4) was used to calculate the lower SO_2 limit, 0.30 ppm (column 5; Eq. 12). Since the measured SO_2 concentration for this hour, 0.04 ppm (column 3), is less than this, the O_3 model should be used for this hour. The O_3 impact is 0.0010 (column 8). Cumulative impact was calculated as an O_3 equivalent impact (column 10). The cumulative impact for hours 7 through 12 of this day was 0.0018, resulting in a z value of −3.773 (column 11; Eq. 27) and an expected injury of only 0.008% (column 12).

Since the thirteenth hour SO_2 concentration of 0.96 ppm is greater than the upper SO_2 limit of 0.69 ppm (column 6), the SO_2 model (Eq. 23) should be used for this hour, resulting in an SO_2 impact of 0.81 (column 7). The z of −3.773 (column 11) at the end of the previous hour was used to calculate an equivalent I_1 of 0.043 (Eq. 32). The I_1 of 0.81 for the thirteenth hour was added to this. A z_1 of −1.575 for the cumulative impact (column 11) was then calculated (Eq. 26). This z was used to calculate (Eq. 33) an equivalent cumulative I_2 of 0.071 (column 10). This procedure was followed for the 12 daytime hours of that day and resulted in an expected cumulative injury to the soybean leaves of 7.7%.

SO_2 injury of 6.7% (column 7) plus O_3 injury of 0.19% (column 8) totals 6.9%, slightly less than the 7.7% (column 10) obtained when the two-pollutant model is used to predict percent injury during hours when concentrations are within its limits.

In this study, impact for each daytime hour has been calculated only as a function of SO_2 and O_3 concentrations for that hour. Future studies might explore the possibility of calculating each hour's impact as a function of additional variables such as time of day, light intensity, temperature, soil moisture, and plant age.

An Acute-Chronic Leaf Injury Model

Only acute O_3 concentrations ranging from 0.25 to 1 ppm for exposures ranging from 0.75 to 3 h for Lee 68 and Dare soybeans have been considered so far. Eq. 18 was used to calculate (Table IV, column 6, run 6) and plot (Figure 7) expected leaf injuries at the intersections of these acute concentration and time ranges. Only these four acute data points were used in these acute-chronic regression analyses; otherwise, too many acute data points would have overwhelmed the chronic data.

Chronic leaf injury data for Dare soybean were plotted, listed, and regressed, together with the four acute data points mentioned above, for O_3 concentrations of 0.05 and 0.10 ppm for exposures of 120 h (8 h/day, 5 days/week for 3 weeks),[16] 258 h (6 h/day for 43 days),[17] and 552 h (6 h/day for 92 days).[17] These controlled, chronic concentration exposures were conducted in field exposure chambers. The injury equation parameters calculated by regressing these acute and chronic data together (Table IV, line 2, columns 10–12) are quite similar to the parameters calculated by using only acute data (line 1). This suggests that parameters calculated from only acute exposure data might be used to make a first approximation of leaf injury expected from chronic exposures.

Substitution of the acute-chronic parameters into Eq. 15 gives a Dare soybean leaf injury equation that can be used for either acute or chronic O_3 exposures.

$$z = -0.828 + 0.4876 \ln (c_{O_3}{}^{2.618} t) \qquad (35)$$

The methods used to calculate cumulative leaf injury for one day (Table III, columns 7–10) were applied to the second and third quarters of 1977 for the same site to produce exactly the same type of information, but for these longer periods (Table V, columns 21–24). The acute-chronic parameters for O_3 were used, as shown in the last line of the table heading. (For uniform month length and computational ease, the

Table IV. Observations and calculated injury equation parameters for Lee 68 and Dare soybeans exposed acutely and for Dare soybean exposed chronically to O_3.

Plant (1)	Exposure duration, h (2)	Conc, ppm Poll 1 (3)	Conc, ppm Poll 2 (4)	Leaf injury, % (5)	Number of deviat, z (6)	Run (7)	Number of pollutants (8)	Number of data points (9)	Pollutant 1 Geometric mean, ppm (10)	Pollutant 1 s_g (11)	Injury eqn slope on axis Time (12)	Injury eqn slope on axis P2 conc (13)	Multiple correl coeff (14)
2.10	Leaf injury in soybeans exposed acutely to O_3						1	30	.988	1.932	-.396		.925
2.20	Leaf inj in soybean exposed acutely & chronically to O_3						1	10	1.067	2.189	-.382		.956
2.30	Growth suppression in soybean exposed chronically to O_3						1	8	.789	1.875	-.354		.897
2.20	.75	.25	.00	1.19	-2.26	6	1						
2.20	.75	1.00	.00	43.85	-.15	6	1						
2.20	3.00	.25	.00	7.69	-1.43	6	1						
2.20	3.00	1.00	.00	75.14	.68	6	1						
2.20	120.00	.05	.00	13.00	-1.13	7	1						
2.20	120.00	.10	.00	24.00	-.71	7	1						
2.20	258.00	.05	.00	13.00	-1.13	8	1						
2.20	258.00	.10	.00	38.00	-.31	8	1						
2.20	552.00	.05	.00	19.00	-.88	8	1						
2.20	552.00	.10	.00	37.00	-.33	8	1						
2.20	Leaf inj in soybean exposed acutely & chronically to O_3						1	10	1.067	2.189	-.382		.956
2.30	120.00	.05	.00	1.80	-2.10	7	1						
2.30	120.00	.10	.00	21.00	-.81	7	1						
2.30	258.00	.05	.00	24.50	-.69	8	1						
2.30	258.00	.10	.00	64.90	.38	8	1						
2.30	552.00	.05	.00	19.80	-.85	8	1						
2.30	552.00	.10	.00	51.30	.03	8	1						
2.30	798.00	.05	.00	21.60	-.79	8	1						
2.30	798.00	.10	.00	64.80	.38	8	1						
2.30	Growth suppression in soybean exposed chronically to O_3						1	8	.789	1.875	-.354		.897

Data sources:
Run 6 (column 7) z values (column 6) were calculated with Eq. 15 by using the parameters in line 1 above (columns 10-12)
Run 7 from Tables 1 and 2 in Ref. 16
Run 8 from Table 1 in Ref. 17

months listed 4 through 9 are actually the fourth through ninth 30 day periods of 1977.)

Two 90 day "growing seasons" (months 4–6 and 7–9) are shown in Table V. Soybean would not actually have been growing in month 4 (April). In order to analyze more ambient concentration data, Table V displays example results for two separate crops in one year rather than just the actual growth months for one soybean crop.

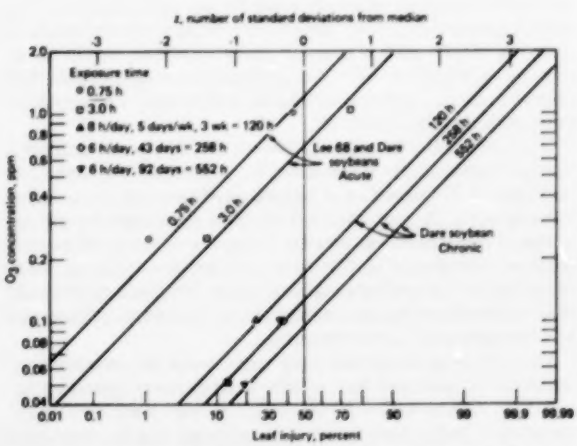


Figure 7. Percent leaf injury in Lee 68 and Dare soybeans exposed acutely (0.75–3 h) and Dare soybean exposed chronically (120–552 h) to O_3.

Comparisons with the NAAQS Three Hour SO_2 Standard

The NAAQS specify that the 3 h average SO_2 concentration shall not exceed 0.50 ppm more than once a year.[18] When monthly maxima (Table V, column 5) remain below the standard (e.g., month 8, 0.467 ppm), no more than 1% leaf injury due to SO_2 (column 21) or 2% due to the combined effects of SO_2 and O_3 (column 23, month 5) is calculated when the impact of each daytime hour is determined, accumulated, and transformed to estimated percent leaf injury. When the monthly 3 h maximum reached 0.72 ppm (month 4), with a peak of 0.99 ppm (column 4), 26% leaf injury was calculated (column 21). Thus, these calculations suggest that no significant visible injury to these Lee 68 and Dare soybeans would be expected due to SO_2 from this power plant if ambient concentrations always remained below the 3 h standard. Future field studies are needed to determine the accuracy of this prediction and how it should be revised.

During months when SO_2 was below the standard (months 5–8), calculated injury was due almost completely to O_3 (column 22). SO_2 alone (column 21) and the combined effects of SO_2 and O_3 (column 23) contributed very little to the total injury estimated (column 24).

Comparisons with the NAAQS One Hour O_3 Standard

The NAAQS specify that a 1 h average O_3 concentration of 0.12 ppm shall not be exceeded on more than one day a year (averaged over several years).[19] This concentration was exceeded only in month 7 (Table V, column 7), when the maximum hour concentration was 0.145 ppm and 19% leaf injury

Table V. Leaf injury estimated from ambient 6:00 a.m.-6:00 p.m. concs of SO_2 (pollutant 1) and O_3 (pollutant 2).
Year 1977 P1 concs are from site 441540020N02, 2.0 mi NE of Johnsonville steam plant, Humphreys Co., TN.
Year 1977 P2 concs are from site 442540011G01, 1015 Trinity Lane, Nashville, TN.
The leaf injury parameters used are for Dare soybean: GMH1= 1.453 ppm, SGD1= 1.293, SLT1= -.189, GMH2= 1.067 ppm, SGD2= 2.189, SLT2= -.382, GMHP1= .874 ppm, SGDP1= 2.044, SLT2P= -.542, SLP2= -.689.

			Conc, ppm, by averaging time												Leaf injury, %, calculated from							
			Maximum						Mean of daily Maxima						Max conc		Mean of Max.		H by h concs for pollutant			
	% h avail		Pollutant 1			Pollutant 2			Pollutant 1			Pollutant 2			Pollutant 1		Pollutant 2					
Month.	P1	P2.	1 h	3 h	7 h.	1 h	3 h	7 h.	1 h	3 h	7 h.	1 h	3 h	7 h	12 h	1 h	3 h.	7 h	12 h.	1	2	1,2	Total
(1)	(2)	(3).	(4)	(5)	(6).	(7)	(8)	(9).	(10)	(11)	(12).	(13)	(14)	(15)	(16)	(17)	(18).	(19)	(20).	(21)	(22)	(23)	(24)
4	98	98	.990	.720	.404	.075	.072	.066	.241	.157	.076	.040	.038	.034	.024	7	3	3	2	26	7	7	30
5	100	100	.590	.373	.279	.090	.085	.077	.135	.089	.051	.057	.054	.048	.034	0	0	9	6	0	12	2	13
6	100	100	.480	.400	.286	.110	.097	.083	.151	.101	.058	.059	.056	.049	.036	0	0	9	7	0	13	1	13
4-6	99	99	.990	.720	.404	.110	.097	.083	.176	.116	.061	.052	.049	.044	.031	7	3	17	13	28	24	14	39
7	98	100	.500	.390	.276	.145	.135	.119	.156	.093	.050	.068	.064	.055	.039	0	0	12	9	0	19	3	20
8	100	100	.640	.467	.266	.090	.088	.076	.206	.135	.084	.025	.023	.018	.013	0	0	0	0	1	5	1	7
9	100	49	.980	.707	.370	.095	.083	.070	.152	.094	.047	.041	.039	.034	.024	6	2	2	1	8	4	3	14
7-9	99	83	.980	.707	.370	.145	.135	.119	.171	.107	.060	.045	.042	.036	.026	6	2	10	7	12	24	12	35

was calculated from the impact of all daytime hours (column 22). When the peak hour in a month was as low as 0.09 ppm (month 5), 12% leaf injury was calculated. Leaf injuries totaling 24% were calculated for a 90 day growing season (months 4–6) when concentrations always remained below the NAAQS for O_3, a maximum 1 h concentration of 0.12 ppm (column 7). (The value of 24% may be an overestimate which should be checked in future experiments.) These calculations suggest that the present O_3 standard of 0.12 ppm does not protect Lee 68 and Dare soybeans from significant visible leaf injury.

Table VI. Leaf injury and growth suppression estimated for Dare soybean and crop yield reduction estimated for Corsoy soybean for plants exposed either to a mean O_3 conc or to each daytime hour's O_3 conc measured in Nashville, TN, during months 4-6 and 7-9 of 1977.

		Mean of daily maximum 7 h avg	Effect, %, est if plants exposed 7 h/day to this O_3 conc					Effect, %, est from the impact of each daytime h O_3 conc for 90 days	
			For col 2 % of 90 days		For 58.5 days				
Months	% h avail	O_3 concs, ppm	Leaf injury	Growth suppression	Leaf injury	Growth suppression	Corsoy crop yield reduc	Leaf injury	Growth suppression
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
4-6	99	0.044	17	16	13	11	13	24	25
7-9	83	0.036	10	8	8	6	8	24	26

A Chronic Growth-Suppression Model

Growth-suppression data, expressed as percent reduction in plant fresh weight relative to a control, are available for Dare soybean exposed for 120 h (8 h/day, 5 days/week for 3 weeks)[16] and for 258, 552, and 798 h (6 h/day for 43, 92, and 133 days, respectively)[17] (Table IV, last 9 lines). When the calculated regression parameters (line 3) are used in a computer program which produces a table like Table V, the growth suppressions listed in column 5 of Table VI are obtained.

A Comparison with Crop Reduction Measurements

Corsoy soybean was raised in open-top field exposure chambers for a growing season, harvested, and the crop yield measured.[8] During the growing season, various O_3 concentrations were added to ambient levels for 7 h each day to give the mean concentrations of the daily maximum 7 h averages plotted in Figure 8. The lowest concentration plotted was 0.022 ppm; this concentration was obtained by filtering ambient air through carbon. If we assume that this low O_3 concentration resulted in a crop yield 2% less than expected at a zero concentration, then the yields averaged over the sets of four chambers with the same concentrations would be as plotted on Figure 8. The O_3 concentration which causes 50% crop reduction, the geometric mean, is 0.10 ppm. The standard geometric deviation is 2.08.

The assumed 2% crop reduction at 0.022 ppm is a mathematical convenience. It was selected to produce a straight line on Figure 8. Expected crop reduction above that expected at a background O_3 concentration could be calculated for a given ambient concentration by first using the line (or its mathematical expression) in Figure 8 to determine expected crop reduction at the ambient concentration. Net reduction would then be obtained by subtracting the crop reduction expected at a background O_3 concentration.

Percent crop reduction may sometimes be roughly proportional to percent leaf injury or to percent growth suppression. Assuming such relationships may hold here, measured crop reductions for Corsoy soybean can be compared with modeled leaf injuries and growth suppressions for Dare soybean (Table VI). (Since different soybean cultivars are

being compared here, exact correspondence is not expected.)

The 4–6 month mean of the daily maximum 7 h O_3 concentrations (Table V, column 15) was 0.044 ppm (Table VI, column 3). If Dare soybean had been exposed to a constant concentration of 0.044 ppm for 7 h/day for 99% (column 2) of this 90 day period, the O_3 one-pollutant model (Eq. 35) predicts that 17% leaf injury (column 4) would have been estimated (Table V, column 19). Note that the constant concentration of 0.044 ppm used in this calculation does not take into account the greater effects expected from hour by hour variations in concentration that predict the 24% leaf injury listed in column 9. Similar calculations predict a growth suppression of 16% (column 5) when using an average concentration and 25% (column 10) when using hour by hour concentrations.

The Corsoy soybean plants were exposed to O_3 for 7 h/day for 55 days and for half that on 7 days,[8] giving an equivalent of 58.5 7 h days, for a total exposure of 409.5 h. The Corsoy soybeans were harvested on October 14, 112 days after planting.

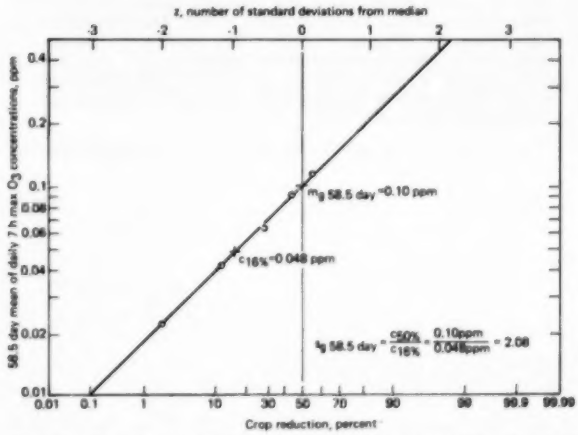


Figure 8. Percent crop reduction for Corsoy soybean exposed to various 58.5 day means of daily 7 h maximum O_3 concentrations.

Corsoy soybean crop yield reduction for an O_3 concentration of 0.044 ppm was calculated for this 58.5 day exposure, using the parameters in Figure 8, to be 13% (column 8). This crop yield reduction value is identical to the value calculated for leaf injury for the same exposure duration (column 6) and close to the calculated value for growth suppression (column 7). For 58.5 days of exposure during months 7–9, crop yield reduction was again identical to the calculated leaf injury value and close to the growth suppression value.

Leaf injuries due to SO_2 (Table V, columns 17, 18) were estimated (Eq. 17) for maximum SO_2 concentrations (columns 4, 5). For this power plant SO_2 point source, means of daily maxima (column 11) calculated for SO_2 predicted no injury during any month. The present SO_2 3 h standard of 0.50 ppm thus appears to be both a good dividing point between expected injury and insignificant injury and a good parameter to use in calculating the potential for some injury for soybean plants near SO_2 point sources. Note, however, that about 2–3 times as much injury is expected from the maximum 1 h concentration as is expected from the maximum 3 h concentration.

Summary

Leaf injury data were analyzed for Lee 68 and Dare soybeans exposed acutely (for 0.75, 1.5, and 3 h) in the laboratory to O_3, SO_2, or both simultaneously, and for Dare soybean exposed chronically (up to 552 h) to O_3 in field exposure chambers. Regression analyses of these data were used to develop a two-pollutant leaf injury mathematical model and to calculate the parameters of best fit for this new model and a previously developed one-pollutant model. In these models percent leaf injury is expressed as its linear Gaussian transform, z, the number of standard deviations from 50% injury. The O_3–SO_2 model explains 88% of the variance in the measured z values. In this two-pollutant model (Eq. 3) z is proportional (Eq. 19) to the logarithm of a new concentration-time variable, impact (Eq. 25). The impact for an hour is SO_2 concentration raised to the 1.845 power times O_3 concentration raised to the 1.271 power. The impact for a day is the summation of the daytime hourly impacts.

The two-pollutant model should be used when the ambient SO_2 concentration for an hour is approximately five times the O_3 concentration. When SO_2 concentrations are above the two-pollutant model limits, a one-pollutant SO_2 model (Eq. 1) should be used. Below the limits, a previously developed one-pollutant model for O_3 (Eq. 2) should be used. The total injury for a day is estimated by using each hour's impact; impact is calculated by using an O_3, SO_2, or O_3–SO_2 model for each hour, depending on the relative concentrations for that hour. The exact boundaries between the models are defined by Eq. 12, 13.

Total leaf injury for a 90 day growing season was estimated by summing the impacts for all daytime hours in a growing season (counting missing concentration measurements as 0). For ambient concentrations measured 2 miles from a coal burning power plant, the one- and two-pollutant models predicted, for Dare soybean, that SO_2 concentrations would not cause significant leaf injury near such a point source if 3 h average SO_2 concentrations always remained below the NAAQS of 0.50 ppm. The opposite would hold for O_3. Leaf injuries up to 24% were predicted over a 90 day growing season when concentrations always remained below the NAAQS for O_3, a 1 h maximum of 0.12 ppm.

Percent leaf injury and percent growth suppression estimated for Dare soybean exposed to ambient concentrations over a growing season were quite close to percent crop reduction measured for Corsoy soybean.

Calculations based on ambient concentration data suggest that the O_3 concentration parameter currently used (the growing season mean of the daytime daily maximum 7 h running averages) is a good parameter to use with crop reduction measurements. The SO_2 maximum 3 h average concentration appears to be a good indicator of potential SO_2 injury to leaf surfaces.

References

1. R. I. Larsen, "An air quality data analysis system for interrelating effects, standards, and needed source reductions," *JAPCA* **23:** 933 (1973).
2. R. I. Larsen, "An air quality data analysis system for interrelating effects, standards, and needed source reductions—part 2," *JAPCA* **24:** 551 (1974).
3. R. I. Larsen, W. W. Heck, "An air quality data analysis system for interrealting effects, standards, and needed source reductions: part 3. vegetation injury," *JAPCA* **26:** 325 (1976).
4. R. I. Larsen, "An air quality data analysis system for interrelating effects, standards, and needed source reductions: part 4. a three-parameter averaging-time model," *JAPCA* **27:** 454 (1977).

5. R. I. Larsen, D. E. Gardner, D. L. Coffin, "An air quality data analysis system for interrelating effects, standards, and needed source reductions: part 5. NO_2 mortality in mice," *JAPCA* **29:** 133 (1979).
6. R. I. Larsen, T. C. Curran, W. F. Hunt, Jr., "An air quality data analysis system for interrelating effects, standards, and needed source reductions: part 6. calculating concentration reductions needed to achieve the new national ozone standard," *JAPCA* **30:** 662 (1980).
7. A. S. Heagle, J. W. Johnston, "Variable responses of soybeans to mixtures of ozone and sulfur dioxide," *JAPCA* **29:** 729 (1979).
8. W. W. Heck, O. C. Taylor, R. Adams, G. Bingham, J. Miller, E. Preston, L. Weinstein, "Assessment of crop loss from ozone," *JAPCA* **32:** 353 (1982).
9. Avram Goldstein, "The Logarithmic Transformation and the Log Dose-Response Curve," in *Biostatistics*, Macmillan, New York, 1964, p. 147.
10. P. J. O'Gara, "Sulphur dioxide and fume problems and their solutions," *J. Ind. Eng. Chem.* **14:** 744 (1922).
11. M. D. Thomas, G. R. Hill, Jr., "Absorption of sulfur dioxide by alfalfa and its relation to leaf injury," *Plant Physiol.* **10:** 291 (1935).
12. R. Guderian, H. van Haut, H. Stratmann, "Probleme der Erfassung und Beurteilung von Wirkungen gasfoermiger Luftverunreinigungen auf die Vegetation," *Z. Pflanzenkrankh. Pflanzenshutz* **67:** 257 (1960).
13. R. Zahn, "Untersuchungen uber die bedeutung Kontinuierlicher und intermittierender Schwefeldioxideinwirkung fuer die Pflanzenreaktion," *Staub* **23:** 343 (1963).
14. W. W. Heck, D. T. Tingey, "Ozone. Time-Concentration Model to Predict Acute Foliar Injury," in *Proceedings of the Second International Clean Air Congress*, H. M. Englund, W. T. Beery, eds. Academic Press, New York, 1971, p. 249.
15. W. W. Heck, R. I. Larsen, A. S. Heagle, "Measuring the Acute Dose-Response of Plants to Ozone," in *Crop Loss Assessment*, P. S. Teng, S. V. Krupa, proceedings coordinators, University of Minnesota, St. Paul, 1980, p. 32.
16. D. T. Tingey, R. A. Reinert, C. Wickliff, W. W. Heck, "Chronic ozone or sulfur dioxide exposures, or both, affect the early vegetative growth of soybean," *Can. J. Plant Sci.* **53:** 875 (1973).
17. A. S. Heagle, D. E. Body, G. E. Neely, "Injury and yield responses of soybean to chronic doses of ozone and sulfur dioxide in the field," *Phytopathology* **64:** 132 (1974).
18. "National primary and secondary ambient air quality standards," *Federal Register* **36:** 8186 (1971).
19. "National primary and secondary ambient air quality standards; revisions to the National Ambient Air Quality Standards for photochemical oxidants," *Federal Register* **44:** 8202 (1979).

Dr. Larsen is an environmental research engineer in the Environmental Operations Branch, Meteorology and Assessment Division, Environmental Sciences Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC 27711. Dr. Heagle is a plant pathologist and Dr. Heck is a plant physiologist and research leader, Southern Region, Agricultural Research Service, U.S. Department of Agriculture. Dr. Heagle is in the Plant Pathology Department and Dr. Heck is in the Botany Department, North Carolina State University, Raleigh, NC 27650. This paper was submitted for review in May 1982; the revised manuscript was received December 1982.